

Development of a 670 GHz Extended Interaction Klystron Power Amplifier

David Chernin

Science Applications International Corp.
McLean, VA 22102
chernind@saic.com

**Richard Dobbs,
Mark Hyttinen, Albert Roitman,
Dave Berry**

Communications and Power Industries
Georgetown, Ontario L7G 2J4

Monica Blank

Communications and Power Industries
Palo Alto, CA 94304

**Khanh Nguyen, Vadim Jabotinsky,
Dean Pershing, Edward Wright**

Beam-Wave Research, Inc.
Bethesda, MD 20814

Jeffrey Calame, Baruch Levush

Naval Research Laboratory
Washington, DC 20375

Jeffrey Neilson

Lexam Research
Redwood City, CA 94062

Frank Maiwald, Todd Gaier

Jet Propulsion Laboratory
Pasadena, CA 91109

N. Scott Barker, Robert Weikle

University of Virginia
Charlottesville, VA 22904

John Booske

University of Wisconsin
Madison, WI 53715

Abstract: *We describe our progress on the development of extended interaction klystron amplifiers operating at 670 GHz, meeting demanding requirements for output power, gain, bandwidth, and efficiency.*

Keywords: extended interaction klystron; R/Q; sub-millimeter; beam stick; ladder circuit; EDM

Introduction

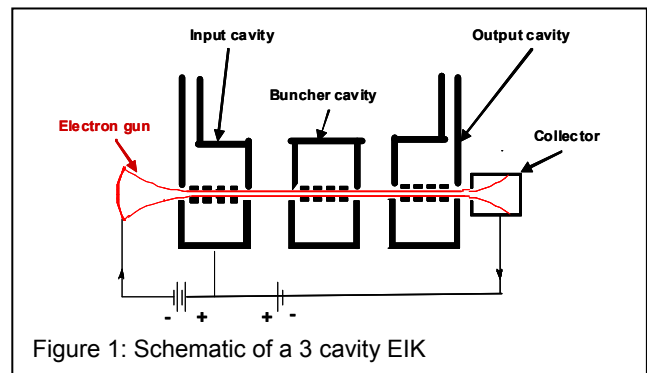
Extended interaction klystrons (EIKs) employ resonant sections of a periodic structure in order to increase the interaction between the beam and the circuit, compared to that achievable in a conventional klystron using a single gap per cavity and the same beam. EIKs have been demonstrated at frequencies up to 218 GHz CW and 229 GHz pulsed. Using modern fabrication techniques, the relatively simple circuit structures employed in these devices may be produced for use at much higher frequencies, including the sub-millimeter and terahertz ranges. Recent examples of millimeter wave EIK designs have been described by Shin, et. al [1], Roitman, et. al., [2], and Toreev et.al. [3]. An overview of the state of the art in millimeter and sub-millimeter EIKs as of mid-2007 is given by B. Steer, et. al. [4]. Hyttinen, et. al. [5] have designed, built, and demonstrated a 9W CW EIK at 218.35 GHz. Amplifier gain is 23 dB, bandwidth is 0.4 GHz, and power added efficiency is 0.50%.

A schematic of a 3 cavity EIK is shown in Figure 1. The basic principles of operation are identical to those of a conventional klystron, i.e. the input cavity produces a velocity modulation on the beam, which develops into density modulation as the beam propagates from input to output. The multi-gap structure of the EIK cavities increases the strength of beam-wave interaction as compared with a single gap, as measured by the quantity $R/Q = V^2 / (2\omega U)$ where V is the decelerating voltage

seen by the beam, ω is the angular frequency of the wave, and U is the energy stored in the cavity. Since both V and U are approximately proportional to the number of gaps, R/Q increases approximately proportionally to the number of gaps. The number of gaps in any one cavity is limited by stability and other considerations. Large values of (R/Q) translate into large values of the gain-bandwidth product.

It is this enhancement of (R/Q) that, in part, makes EIKs especially attractive for high frequency applications. In particular, since the circuit and beam tunnel both necessarily become smaller as the operating frequency is increased, the amount of current that can be propagated through the beam tunnel is reduced. Large values of (R/Q) help compensate for this reduced current. Furthermore, the relatively large values of (R/Q) and the resulting large gain per unit length make for shorter circuit lengths, which are consequently easier to fabricate and align. For these reasons, the EIK is an excellent candidate for development and application as an amplifier in the sub-millimeter and higher range of frequencies.

In this paper we describe our efforts to develop an EIK operating at a central frequency of 670 GHz ($\lambda_0 \sim 0.447$ mm) and meeting certain ambitious RF performance metrics for power, gain, bandwidth, and power added



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efficiency. In order to meet these metrics, the development has proceeded in stages, including a (1) beam stick, (2) low gain, narrow bandwidth EIK, (3) high gain, narrow bandwidth EIK., and (4) high gain, wide bandwidth EIK.

Beam Stick Development

A beam stick is an assembly consisting of an electron gun, a drift tube, a collector, and a focusing magnet. No RF components are included, but the beam parameters (voltage, current, diameter) are those determined by the amplifier design. There is a basic tradeoff between beam tunnel size and beam current: the larger the beam tunnel, the more current may be propagated through it, but the weaker the interaction of each electron with the circuit. The beam tunnel diameter must be small enough, however, provide RF isolation between cavities.

For sub-millimeter devices, a new ‘emittance dominated’ beam regime is encountered in the design of the electron gun, in which the cathode temperature and surface roughness, rather than space charge force, are the primary determinants of the achievable minimum beam size. This fact alone greatly complicates design of the gun and rules out the direct frequency scaling of lower frequency device designs to this frequency regime. Consequently we are compelled to back off from a pure scaled design and accept certain compromises in RF performance.

Using the MICHELLE beam optics code [6], we have designed a high compression electron gun, as illustrated in Figure 2. This gun can produce approximately 100mA at 25kV in a beam diameter of about 0.004”, corresponding to a current density of nearly 800 A/cm². The fill factor is approximately 0.8, but there is significant amount of beam scalloping, due to thermal effects. This scalloping greatly reduces the effective fill factor, and thereby greatly reduces the gain from what could be obtained with an ideal, perfectly laminar beam. An alternative design using a beam scraper could increase the average fill factor, but the requirement of high operating efficiency rules this out. The mod anode design permits operation over a range of current

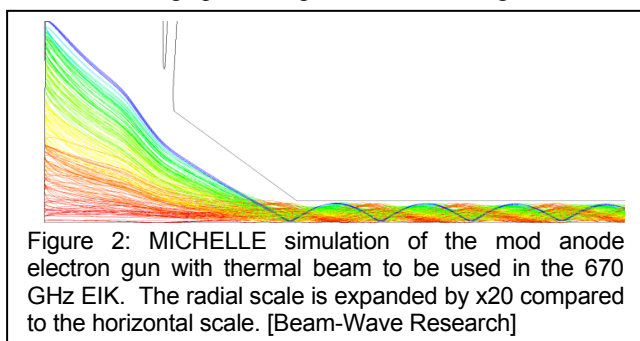


Figure 2: MICHELLE simulation of the mod anode electron gun with thermal beam to be used in the 670 GHz EIK. The radial scale is expanded by x20 compared to the horizontal scale. [Beam-Wave Research]

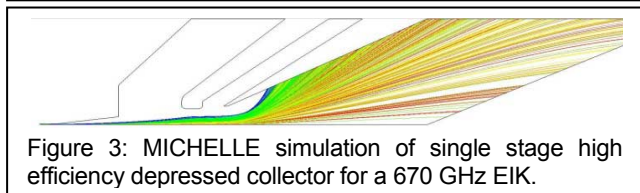


Figure 3: MICHELLE simulation of single stage high efficiency depressed collector for a 670 GHz EIK.

and voltage without loss of beam focus. This feature will allow adjustment of the gun operating parameters to help meet our RF performance goals (See below).

The beam tunnel length in the beam stick was chosen to be approximately 0.685”. The beam tunnel was produced by machining two ‘half-tunnels’ in copper alloy blanks and diffusion bonding the blanks together to form the complete tunnel. However, this technique has proven to be difficult to carry over to an EIK circuit, in which the circuit thickness is only ~0.011”. We consequently plan to use sink EDM (electrical discharge machining) to produce the beam tunnel in a blank in which the complete ladder circuit has been pre-machined. Use of sink EDM in this way limits the achievable length of beam tunnel, however. Our best result to date for ~Ø.005” is approximately 0.790”, though a new generation of EDM machines shows promise of greatly extending this limit.

Use of a highly depressed collector will be essential to meet the amplifier efficiency goal of 0.75%. A single-stage depressed collector with a non-collecting grading electrode has been designed to achieve a collection efficiency of 99% under DC operation. A trajectory plot of the beam in this collector is shown in Figure 3.

A single ‘doughnut’ shaped magnet fits over the gun end of the beam stick. It will maintain a magnetic field of ~1.1 T over the length of the beam tunnel. The cathode is shielded from the magnetic field.

The beam stick has now been fabricated and assembled. A photo of the completed beam stick is shown in Figure 4. At this writing the beam stick is being pumped down in preparation for testing. We expect to have data on beam propagation and collector efficiency and comparisons with simulations to present at the conference.

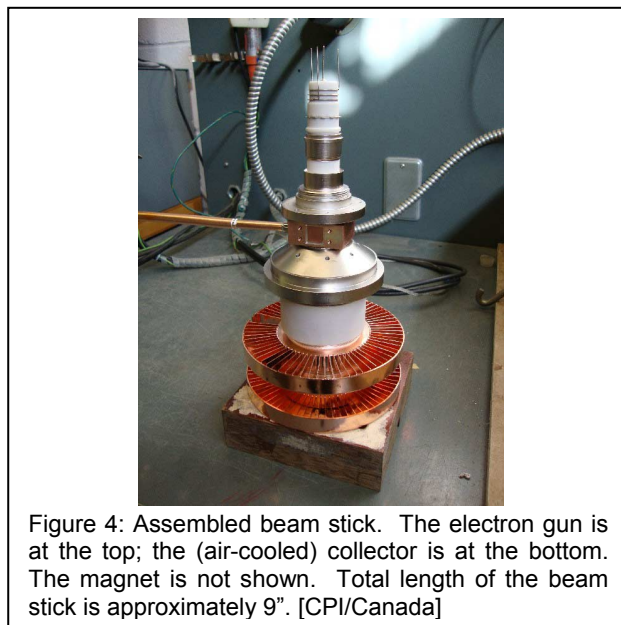


Figure 4: Assembled beam stick. The electron gun is at the top; the (air-cooled) collector is at the bottom. The magnet is not shown. Total length of the beam stick is approximately 9”. [CPI/Canada]

670 GHz EIK Development

The basic RF performance goals for our 670 GHz EIK are listed in Table 1. We note in particular the large bandwidth requirement, in excess of 2.2%. In order to meet these goals, we have adopted an incremental approach in which we are designing and building two EIK's of increasing performance. The first of these, which we call EIK-1a, is a 5 cavity design, the length of which was largely set by our ability – since improved -- to drill the beam tunnel using sink EDM. The beam tunnel length is 0.580". The second EIK, EIK-1b, has been designed to meet or exceed all of the performance goals in Table 1, except bandwidth. EIK-1b is a 6 cavity design, with a total circuit length of 0.750". EIK-1a has been designed to produce 45 mW, with a 1 mW input signal at 670 GHz; EIK-1b has been designed to produce approximately 1W with the same input. Both EIK-1a and 1b will be synchronously tuned, narrowband devices, with 3dB bandwidths of approximately 1 GHz.

Table 1. 670 GHz EIK Performance Goals

Parameter/Unit	Value
P _{out} (CW)/dBm	27
Gain/dB	23
Power added efficiency/%	0.75
Instantaneous bandwidth/GHz	15

The 2.2% bandwidth goal is probably the single most challenging goal for an EIK. One conventional approach to achieving high bandwidth at lower frequencies is to use stagger tuned cavities, but we have been unable to find a practical design, due largely to the sensitivity of a stagger-tuned design to beam scalloping. The reason for this sensitivity is that in a stagger-tuned circuit each cavity is designed to provide gain within a certain portion of the total bandwidth. Consequently, the gain in each portion of the band will depend on whether the scalloped beam happens to bring beam electrons close to or far from the associated cavity. At sub-millimeter wave frequencies, this sensitivity can be extreme. An alternative approach could,

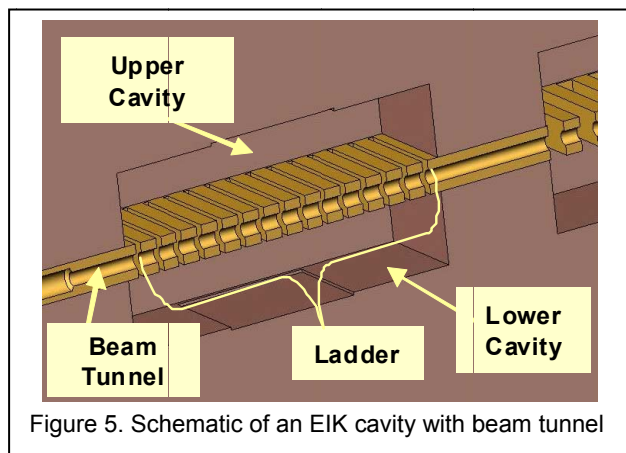


Figure 5. Schematic of an EIK cavity with beam tunnel

in principle, employ identical gain cavities, but exploit multiple resonances in each to achieve large bandwidth. As of this writing, however, we have not found a workable design employing this 'multi-mode' approach at 670 GHz¹.

For the high gain, narrow band 670 GHz EIKs we will employ cavities composed of sections of a ladder structure, as illustrated in Figure 5. These structures are used in millimeter wave EIKs and are expected to be suitable for use in the sub-millimeter range as well, due to their geometrical simplicity, large effective R/Q , and good structural and thermal properties.

The choice of the number of cavities and the number of gaps per cavity is determined by the required gain and output power, as well as by practical constraints imposed by the ability to produce a high quality (straight, round) beam tunnel of the required length. The number of gaps in any one cavity may also be limited by mode distortion and/or spurious modes caused by fabrication errors [7].

Ohmic dissipation in the circuit will not only be large at sub-millimeter frequencies, but will also be sensitive to surface finish, since the skin depth is comparable to surface feature sizes. For example, the skin depth in copper at 670 GHz is ~80 nm. It will be important, therefore, to achieve the best possible surface finish on the interior of the ladder slots, where RF currents are large. Measurements of the surface resistivity of copper are underway at the University of Wisconsin using a quasi-optical cavity. They have found an approximately linear relationship between surface conductivity at 650 GHz and surface roughness, over a range of surface roughness from about 5 nm to 800 nm and corresponding conductivity values of 0.79 to 0.24 times the DC conductivity of copper (5.69×10^7 S/m), respectively.

Since large ohmic losses lead to large attenuation rates in fundamental mode waveguide (approximately 1.4 dB/inch at 670 GHz in WR1.5 guide, assuming $0.5 \times$ copper DC conductivity), we will employ Gaussian mode quasi-optical input and output couplers. Our designs indicate that we can achieve ~ 0.2 dB loss between the input (output) flange and the input (output) cavity aperture using tapered Gaussian mode couplers and CVD diamond windows.

Figure 6 shows a sample ladder fabricated using a combination of sink and wire EDM. We expect the surface

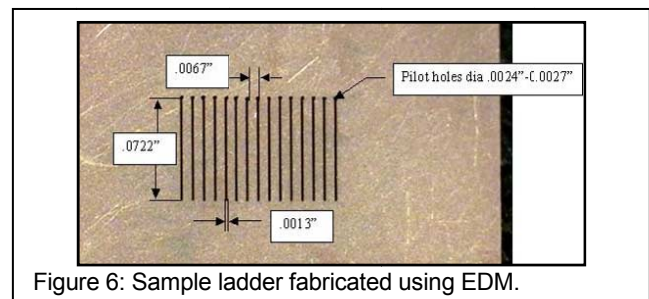


Figure 6: Sample ladder fabricated using EDM.

¹ CPI/Canada has demonstrated 2.4% bandwidth at W-band using a staggered tuned modulating section and a multi-mode output cavity [4].

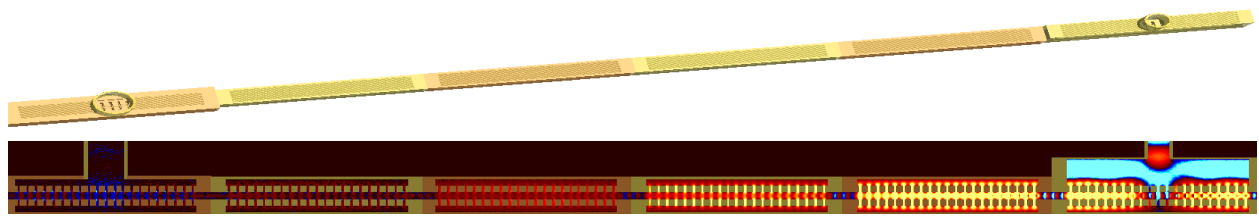


Figure 7: MAGIC-3D simulation of EIK-1b. The colors in the lower figure correspond to values of the axial electric field.

finish of the interior of the slots, where the RF currents are largest, to be of the order of 1000nm; in our design studies we have used a surface conductivity of approximately 1/6 of the DC conductivity of copper, consistent with the U. Wisconsin measurements. Total dissipation on the circuit will be due to a combination of RF dissipation and beam interception, both of which will be largest near the output.

Future development of EIK's at even higher frequencies may have to rely on lithographic (LIGA) techniques to fabricate precision circuits with very high quality surface finish in order to minimize loss. One practical difficulty of this approach is that only certain metals can be electro-deposited on the lithographically formed 'mold' of polymer resist. The most obvious choice is pure oxygen-free copper, but copper parts can suffer from metal fatigue and/or dimensional distortions due to grain growth during thermal cycling, which can in turn lead to device failure. We are investigating methods to electro-deposit certain copper alloys that may be more suitable for this application.

We have relied heavily on computer simulation using the 3D particle-in-cell code MAGIC-3D to design our EIK circuits. Though individual runs can be many hours long, the accuracy of the simulation is expected to be very good, due to the detailed representation of the circuit structure and the beam-wave interaction. An example of a simulation for EIK-1b is illustrated in Figure 7. Results from many runs for output power vs. frequency are shown in Figure 8. We note the narrow band width (~ 1 GHz) and high gain (~ 30 dB) predicted for this design. Additional simulation results will be presented at the Conference.

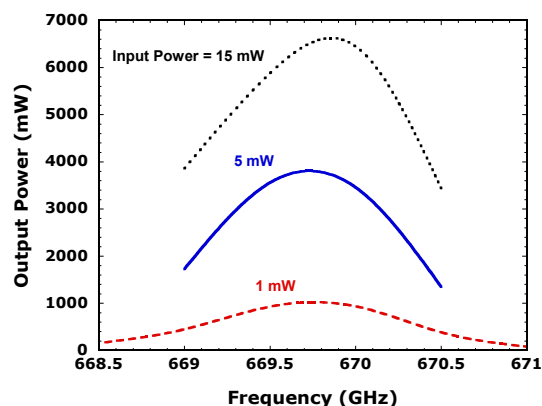


Figure 8: Predicted output power vs. frequency for EIK-1b, for different values of input power.

Summary

We are developing extended interaction klystrons operating at a center frequency of 670 GHz. A beam stick and two high gain, narrowband EIKs have been designed and are being fabricated; achieving both high gain and broad bandwidth in the same design remains a difficult problem. The main challenges in design include focus and transport of an emittance dominated electron beam and the development of a low loss, broadband, high gain circuit. The main challenges in fabrication and integration include achieving required component dimensions and alignment within specified tolerances and achieving high quality surface finishes using materials with satisfactory mechanical and thermal properties.

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